Satellite Derivation of Ocean-Atmosphere Heat Fluxes in a Tropical Environment

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ABSTRACT

Satellite estimates of ocean/atmosphere heat fluxes were compared with surface measurements taken at John Brewer Reef (18°38'S, 147°E) located 80 km NNE of Townsville, Australia. For a 45 week period all the components of the surface heat fluxes : net radiation, sensible and latent heat fluxes, were estimated from surface observations and averaged on a weekly basis. Concurrent satellite observations in the vicinity of John Brewer Reef consisted of GMS visible reflectance data, NOAA-9 soundings of temperature and humidity, and sea surface temperatures derived from a blend of ship observations and NOAA-9 data. Wind estimates were derived from the Darwin Tropical Analysis. All satellite data were tested for their ability to reproduce surface heat fluxes.

The rms differences (measured versus modeled) between the weekly averaged values of net radiation, the turbulent heat flux (sensible plus latent) and the total ocean/atmosphere heat flux were 16 Wm^{-2}, 45 Wm^{-2} and 48 Wm^{-2} respectively. Averaged over the 45 week period, a mean difference of 9 Wm^{-2} (measured-modeled) was obtained for the total ocean-atmosphere heat exchange.

1. Introduction

Large scale studies of ocean/atmosphere heat fluxes are traditionally based upon marine weather reports. However these data sets are scarce in many ocean areas not covered by shipping routes. The reliability of monthly mean fluxes has been questioned in these areas, as biases may result from the inclusion of temporally and/or spatially sparse data (Ramage, 1984; Sarachik, 1984).

It is within this framework that satellite data offer distinct advantages. Geostationary and polar-orbiting satellites cover large areas of the globe at regular intervals, providing information on the state of the atmosphere and ocean. In this study we assess the applicability of satellite data to provide estimates of ocean/atmosphere heat fluxes at a location in the tropical western Pacific ocean. The emphasis has been placed on long term high quality surface measurements as opposed to short term ship estimates from a variety of geographic locations.

The total ocean/atmosphere heat flux (Q_A) may be partitioned into its component fluxes consisting in net radiation (Q^*) and sensible (Q_H) and latent (Q_E) heat fluxes :

$$Q_A = Q^* + Q_H + Q_E \tag{1}$$

In turn the net radiation can be written in terms of the incoming (K_D) and reflected (K_U) solar radiations fluxes and the incoming (L_D) and emitted plus reflected longwave radiation fluxes (L_U) :

$$Q^* = K_D + L_D - K_U - L_U \tag{2}$$

In this study all the terms in equations (1) and (2) with exception of K_U were obtained from direct surface measurements. Similarly satellite data, or satellite related data, were used to estimate all the component fluxes in the above equations.

2. Data acquisition

The measurement period encompassed the dates 1 June 1985 to 1 April 1986 (Figure 1). Measurements were taken from a wooden floating pontoon, anchored to the reef bottom (~7m depth). A tower was constructed on the pontoon and all atmospheric sensors were located free from obstructions and 4.5 m above the platform and 5.5 m above the water. A Campbell CR21X micrologger was used to record all data at a frequency of 0.5 seconds. Table 1 provides details on all the meteorological variables that were measured.

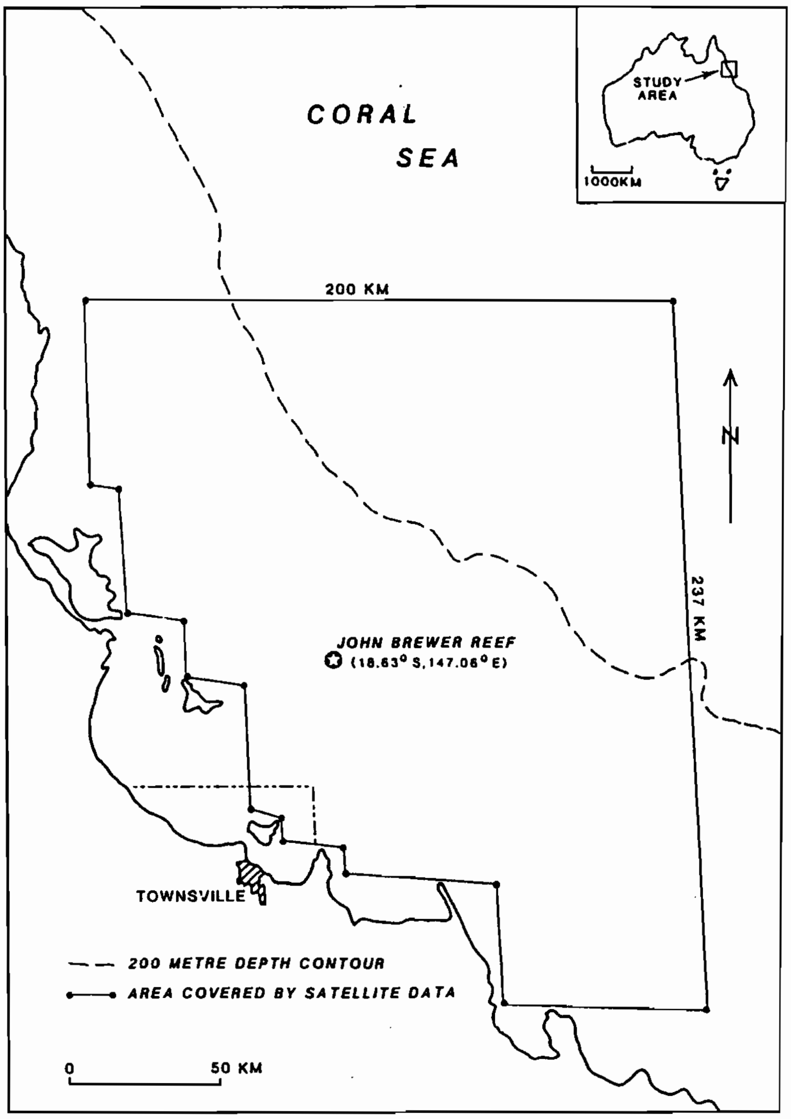

FIG.1. Location of the study region showing the area of GMS coverage and the location of John Brewer Reef.

During the course of the measurement period, there were no weeks with predominantly westerly of southerly winds which would have indicated the presence of air masses of continental origin. The reef coral was only partially exposed (<10 percent) at extremely low tides which occurred infrequently. Measurements of surface water temperature with an infrared radiometer (J. Hacker, Flinders University of South Australia, pers. comm.) have shown the lagoon to be occasionally 0.1 to 0.3°C warmer than surrounding waters.

TABLE 1 Instruments used to measure ocean-atmosphere heat fluxes at John Brewer Reef : 1 June 1985 - 1 April 1986

Instrument	Measured Meteorological Variable	Days Available
Kipp & Zonen pyranometer	(a) incoming solar radiation	225
Eppley precision pyrgeometer	(b) incoming longwave radiation	107
copper/constantan thermocouples	(c) air temperature	225
copper/constantan thermocouples	(d) sea surface temperature	173
Vaisala humidy sensor	(e) relative humidity	225
Met One (3 cup) anemometer and locally built (4 cup) anemometer	(f) wind speed	225

Calculated Fluxes	Relevant Meteorological Variable(s)	Days Available
incoming global radiation	(a)	225
outgoing global radiation	(a)	225
incoming longwave radiation	(b)	107
outgoing longwave radiation	(d)	107
latent heat	(c),(d),(e),(f)	173
sensible heat	(c),(d),(e),(f)	173

Table 2 provides details on satellite and related data that were used to derive the surface heat fluxes. A continuous data set with no missing values would imply a total of 315 days with GMS and NOAA/TOVS and NOAA/AVHRR data. This was not achieved.

Data for the GMS pixel closest to John Brewer Reef was manually retrieved on a daily basis. NOAA/TOVS data containing three levels of precipitable water vapor and 15 levels of air temperature, was obtained from NOAA-NESDIS (Washington, DC) as a TOVS sounding data product. These data were retrieved in a box of 4° x 4° square with John Brewer Reef being located in the southwest corner. On each day all soundings in the square were averaged, with larger weighting applied to those soundings closest to John Brewer Reef.

Sea surface temperatures were extracted from a monthly averaged data set consisting of a blend of ship reports and NOAA-9 multi-channel sea surface temperatures (Reynolds, 1988). An average monthly sea surface temperature was estimated for the study area as a weighted average of the three closest grid points, which were spaced at two degree intervals. These monthly values were temporarily interpolated to provide mean weekly sea surface temperatures. No satellite-derived estimates of near-surface wind were available. In the absence of this important parameter, data from the Darwin Tropical Wind Analysis were substituted. Values from the grid point at 17.5°S, 147.5°E were averaged to estimate at mean weekly wind speed for the study area.

TABLE 2 Satellite and ancillary data used to estimate ocean-atmosphere heat fluxes near John Brewer Reef : 1 June 1985 - 1 April 1986

Data Type	Frequency	Spatial Resolution	Days with at least one observation	Related Heat Fluxe(es)
GMS visible	3 times daily	2.5 x 3 km	303	K_D,K_U,L_D
NOAA/ TOVS	2 times daily	300 x 300 km	209	L_D,Q_E,Q_H
NOAA/ AVHRR plus ship SSTs	monthly	1° x 1°	interpolated weekly	L_U
Darwin Tropical wind Analysis	2 times daily	2.5° x 2.5°	315	Q_E,Q_H

3. Analysis

The following relationships were derived to estimate surface heat fluxes from satellite data.

a. Incoming Global Radiation

A relationship was defined between the daily transmissivity of global radiation (τ) and the satellite-determined earth-atmosphere reflectivity (αE_A). When applied to half the data set the following relationship was obtained :

$$\tau = K_D/K_O = 0.773 - 1.037\ \alpha E_A; \quad \gamma^2 = 0.89 \quad ; \quad S.E. = 0.052 \qquad (3)$$

where K_O is the extra terrestrial global radiation, a function of latitude and time of year. When tested on the remainder of the data, this relation could estimate K_D on a daily basis with a mean difference of -2 Wm^{-2} (measured-predicted) and a rms difference of 28 Wm^{-2}. This rms difference represents an error of 11 percent in the mean measured value of 246 Wm^{-2}.

b. Reflected Solar radiation

The upwelling solar radiation from the water surface (K_U) can be written as :

$$K_U = \alpha_W K_D \qquad (4)$$

Due to measurement problems and the relative insensitivity of this term (Nunez et al., 1972), the albedo term α_W was determined from the tables of Payne (1972) corresponding to a latitude of 20°S. The resulting α_W daily values were 0.07 for May through August and 0.06 for all other months.

c. Incoming Longwave Radiation

The LOWTRAN 6 model for atmospheric transmittance and radiance (Kneizys et al., 1983) was applied on the daily TOVS data for the estimation of L_D.

Reconstruction of the temperature and humidity profiles from TOVS data was based upon the technique of Darnell et al. (1983), modified to include a well mixed planetary boundary layer capped by an inversion. It is physically reasonable to treat the atmospheric structure in this fashion since the area is subjected to winds with large oceanic fetches for most of the study period. No distinction was drawn between winds of northerly and winds of south-easterly origin. Below the inversion the atmospheric features constant potential temperature and specific humidity, except in the surface boundary layer where the air temperature and specific humidity, change to take the characteristics of the ocean surface. Further details are provided in Michael and Nunez (1989).

The LOWTRAN 6 model solves for L_D for totally cloudy (L_{DC}) and cloudless (L_{DO}) conditions. The actual longwave radiation can then be given as :

$$L_D = (1\text{-}C)\, L_{DO} + CL_{DC} \qquad (5)$$

Values of C were derived using GMS visible data and tables presented by Taylor and Stowe (1984) on low level and middle level cloud albedo. Denoting α_L as the minimum satellite reflectivity for the month, and α_H as the threshold reflectance value for totally overcast conditions, the following relations is obtained :

$$C = \begin{cases} 0 & \alpha_{EA} < \alpha_L \\ (\alpha_{EA} - \alpha_L)/(\alpha_H - \alpha_L) & \alpha_L < \alpha_{EA} < \alpha_H \\ 1 & \alpha_H < \alpha_{EA} \end{cases} \qquad (6)$$

Cloud heights were derived from the TOVS cloud top pressure, and assigned fixed pressures of 850 hPa and 750 hPa for low and middle clouds respectively. No TOVS cloud top pressures were consistent with the presence of clouds.

Pyrgeometer measurements were available during the summer and autumn period for a total of 125 days. Of these, there were 107 days with concurrent pyrgeometer and GMS data, and 57 days with additional TOVS data. For this 57 days period, the mean difference produced by the model just described is 5 Wm^{-2} (the model under-predicts) and the rms difference in the daily estimates of L_D is 14 Wm^{-2}.

d. Outgoing Longwave Radiation

This term is mainly dependent on the satellite derived sea surface temperature. Best agreement with surface measurements were obtained from the Reynolds blended shipboard/NOAA AVHRR data set (Reynolds, 1988). The outgoing longwave radiation can be written as :

$$L_U = \varepsilon\theta T_S^4 + (1\text{-}\varepsilon)L_D \qquad (7)$$

where T_S is the surface temperature, θ is the Stefan-Boltzmann constant and ε is the surface emissivity which was taken as 0.97 (Davies et al., 1971).

e. Turbulent Fluxes

Both surface estimates and the satellite technique use the bulk aerodynamic formulae, with stability-dependent bulk transfer coefficients as described by Large and Pond (1982) :

$$Q_E = \rho\, LC_E\, U_a(q_s\text{-}q_a); \qquad Q_H = \rho\, C_P C_H U_a(T_s\text{-}T_a) \qquad (8)$$

where ρ is the air density, L is the latent heat of vaporization of water, C_P is the specific heat of air at constant pressure, C_E and C_H are the bulk transfer coefficients for sensible and latent heat flux respectively, q and T are the specific humidity and temperature at the water surface (subscript "s") and 10 meter height (subscript "a") and U_a is the wind speed at 10 meters.

Using the satellite technique Qs can be readily derived from the surface temperature, and U_a is given by the Darwin Tropical Wind Analysis. The problems is to derive q_a in terms of the precipitable water vapor as obtained from TOVS. Various relationships were tested, including that described in Liu (1986) for 40 stations in the mid-latitude and tropics. Also tested was a simple linear relationship between W (precipitable water vapor) and q_a for John Brewer Breef. The best relationship was obtained by a plot of q_a versus Δq where $\Delta q = q_s - q_a$ is treated as a dependent variable

$$\Delta q = 0.012 - 0.00018 W_o; \quad r^2 = 0.27; \quad S.E. = 0.002 \tag{9}$$

This relationship is statistically significant at the 1 percent level. Equations 8 and 9 were applied for the 26 weeks in which Q_E values were available from measurements at John Brewer Reef. The rms weekly difference is 40 Wm^{-2}, which is considerably lower than the value using the Liu (1988) technique (104 Wm^{-2}) and the W versus q_a linear regression (69 Wm^{-2}).

The lack of success of the polynomial regressions technique of Liu is probably a result of fundamental differences between W supplied by NOAA-9/TOVS and by Nimbus-7/SMMR. To ensure compatibility with radiosonde data, Liu (1988) describes how empirical correction formulae for SMMR W data were determined for monthly or yearly intervals. The TOVS data underwent no similar treatment so that it is possible that they were not representative of the field of W which would have resulted from a network of radiosondes in the study region. However comparison of our TOVS data with radiosonde data from Willis Island (16°8'S; 149°59'E) gave good results. Nevertheless there is need to subject the TOVS data to the same spatial and temporal scales as that applied by Liu to the Nimbus-7 SMMR data. It is likely that a similar relationship will be derived.

The sensible heat flux is a small term in the marine environment. The satellite technique cannot be applied in equation 8 since near surface air temperatures are not available from satellite data. Instead the Bowen ratio technique, which is deemed to be a function of surface temperature (Priestl and Taylor, 1972; Hicks and Hess, 1977) was used. The Bowen ratio can be described as :

$$\beta = 0.79 \,(C_p/L_s) - 0.21 \tag{10}$$

where S is the slope of the saturation specific humidity/temperature curve. The temperature dependence of β comes mainly through S. The sensible heat QH can be given as

$$Q_H = \beta Q_E \tag{11}$$

For each week, the blended sea surface temperature was used to determine the ratio C_p/L_s. β was obtained from equation 10 and applied in equation 11 to determine Q_H.

Few Q_H values exceed 10 Wm^{-2} in magnitude. The mean difference between surface measurements and the predictions was -1.6 Wm^{-2}, and the rms difference was 8.5 Wm^{-2}, of the same magnitude as the average weekly sensible heat flux. At this time scale Q_H are not meaningful, although they are useful in providing an estimate of the correct order of magnitude for the heat balance.

f. Time Series of Weekly Heat Fluxes

Figure 2 shows how the weekly satellite estimates of the turbulent heat fluxes compare with surface measurements. In deriving the net solar radiation flux, equations 3 and 4 were applied to the entire data set. As may be noticed, both measurements and models agree closely in the overall seasonal trend. The net longwave radiation flux is a conservative quantity which does not show a seasonal trend.

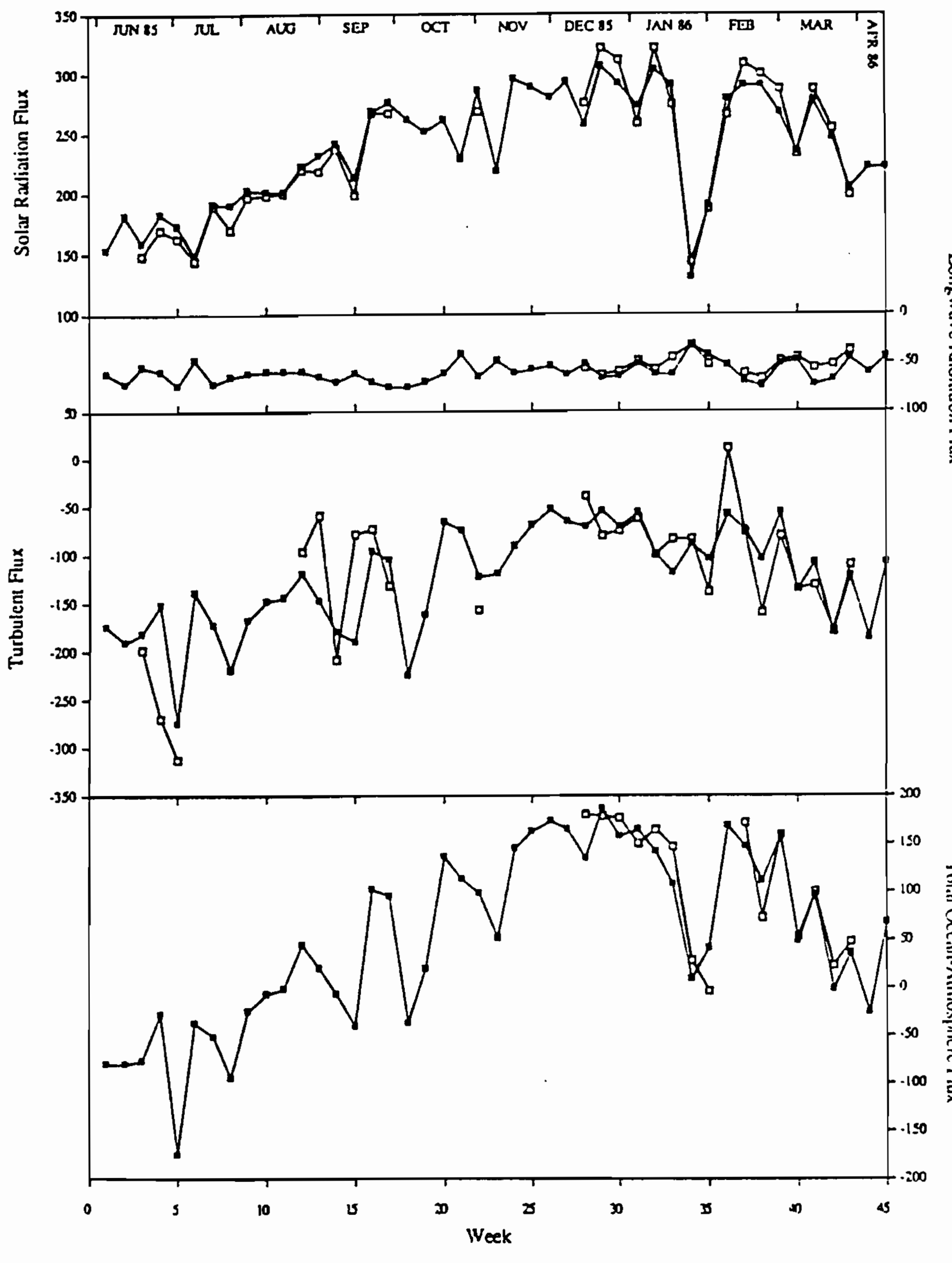

FIG.2. Weekly time series of net solar radiation flux (K*), net longwave radiation flux (L*), total turbulent heat flux (Q_t) and the total ocean-atmosphere heat flux (Q_a). Surface measurements are represented by open squares, and the satellite-derived estimates are drawn as filled squares. Negative heat fluxes imply a heat loss by the ocean. All units are Wm^{-2}.

The form of the variations in outgoing turbulent flux (Q_T) indicate that wind speed is the dominant influence. In winter (June-August) the south-easterly trade winds are strong and the latent heat flux often exceeds 200 Wm^{-2} in magnitude. In summer the northerly winds are moister and lighter; the magnitude of Q_E drops. In March as the winds strengthen, the correspondence between the surface and satellite-bases fluxes is limited, a consequence of the difficulty in reproducing the 10 meter specific humidity.

The total ocean/atmosphere heat flux is dominated by the energy gain by solar radiation and loss by latent heat flux. In winter Q_E is large and Q^* is low so that the ocean is loosing energy. By mid-August the ocean starts gaining energy. This pattern persists until mid-December when a maximum heat gain of 180 Wm^{-2} is reported.

4. Conclusion

In summary, the rms differences (measured versus modeled) between the weekly averaged values of net radiation, the latent heat flux and sensible heat flux were 16, 40 and 21 Wm^{-2} respectively. Combining all these terms, and assuming independence of errors, a rms difference of approximately 48 Wm^{-2} was obtained in the weekly estimate of the total ocean-atmosphere heat flux.

This paper demonstrates that is is feasible to estimate weekly ocean-atmosphere heat fluxes at a point in the ocean based on satellite-derived quantities. Shorter time scales were inaccessible, due to limitations imposed by the sea surface temperature and atmospheric sounding data.

We conclude by advising of the need to test these empirical relationships in other environments and synoptic situations. A general satellite-based method, well calibrated in a number of locations would be a practical and powerful analysis tool.

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